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NASA PROGRAM APOLLO WORKING PAPER NO. 1173

STUDY OF LEM ABORT TRANSFER TRAJECTORIES

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

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STUDY OF LEM ABORT TRANSFER TRAJECTORIES

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SUMMARY

The results of an investigation of the orbital transfer characteristics for LEM aborts from the Hohmann descent transfer and from circular parking orbits attained after aborting from the powered descent and from the lunar surface are presented. The variation of the required characteristic velocity and the time required to complete rendezvous indicates that the present allowances of 500 to 600 fps and 10.5 hours contingency time are sufficient for most abort situations. The exception applies to those aborts from the lunar surface initiated between 1.0 and 2.1 hours after the time for a nominal launch. Aborts during this period may not be completed autonomously by the LEM, but require phasing maneuvers by the CSM.

INTRODUCTION

At any time after LEM separation from the CSM a mission abort may be necessary due to some system failure, for example, life support, descent propulsion, or prime guidance systems. The trajectories necessitated by these aborts are generally divided into two parts: (1) suborbital powered flight, and (2) orbital transfer or coasting flight to intercept and rendezvous with the CSM. These two flight regions are concerned with different operational parameters and hence require separate investigations. It is the purpose of this report to determine only the family of orbital transfer trajectories for LEM aborts during all phases of the landing mission.

In this abort trajectory study calculations are based on the two-impulse conic equations. The trajectories are constrained to have a clear pericynthion altitude of 50 000 feet, a time to rendezvous of less than 10.5 hours, and velocity (fuel) requirements within the LEM ΔV budget. Transfer trajectories for aborts off the Hohmann descent transfer, powered descent, and surface are investigated.

STATEMENT OF PROBLEM

A sketch of the nominal LEM mission is shown in figure 1. The CSM and LEM are initially in a circular parking orbit at 80 nautical miles above the lunar surface. From this orbit, the LEM is separated from the CSM and injected into a Hohmann descent transfer to a pericynthion altitude of 50 000 feet. At this point, the powered descent to the lunar surface is begun by the LEM. After completing the lunar surface mission, the LEM is launched to 50 000 feet in the plane of the orbiting CSM. The launch is terminated with conditions required to insert into a Hohmann ascent transfer to rendezvous with the CSM in the parking orbit.

Assuming an abort decision is necessary any time after LEM separation, there are three possible phases in the nominal mission during which the LEM can inject into an abort trajectory. These phases are: (1) the Hohmann (coasting) descent transfer, (2) powered descent to the lunar surface, and (3) the lunar surface.

Hohmann Descent Transfer Phase

Figure 2 (a) illustrates an abort trajectory from the Hohmann descent phase. Due to the abundance of propulsion (i.e., descent and ascent propulsion) available for an abort during this part of the mission, many types of abort trajectories could be investigated. The two extreme abort trajectories are considered herein: (1) minimum ΔV abort transfer, and (2) high ΔV or quick-time aborts. The first type is required for minimum fuel reference purposes and also indicates aborts that could be performed by the low thrust reaction control system (RCS) if main engine failures necessitate the abort. The quick-time abort illustrates the type of aborts available using the propulsion of either or both the ascent and descent engine. For example, such trajectories may be necessary in the event of a life support system malfunction during this first sustained manned operation of the LEM.

Powered Descent Phase

An abort from the powered descent phase is illustrated in figure 2 (b). First, a continuous powered abort flight back to a circular orbit at 50 000 feet altitude must be performed. At this point, the LEM is inserted into an abort transfer trajectory that will intercept the CSM. It is not the purpose of this report to investigate the sub-orbital phase of this abort, but rather to investigate the transfer phase. Reference powered abort trajectories used for suborbital flight are defined in the section on scope of calculations.

Surface Phase

A surface abort is defined as an anytime launch situation. That is, the CSM may not be at a favorable position for economical (fuel or time) LEM launch to perform intercept and rendezvous. Hence, as illustrated in figure 2 (c), this abort is accomplished in three parts; launch to a parking or phasing orbit, coast in phasing orbit for favorable transfer conditions, and finally, transfer to intercept and rendezvous. Again, a standard or reference suborbital powered launch trajectory is assumed.

SCOPE OF CALCULATIONS

For this study, the circular parking orbit of the Apollo vehicle is the nominal 80-nautical-miles orbit. It is assumed that the LEM lands in the plane of the CSM orbit and, therefore, the aborts off the Hohmann descent transfer and powered descent are planar trajectories. However, due to surface rotation, surface aborts may be initiated up to $\frac{1}{2}^{\circ}$ out of the plane of the orbiting CSM and still be consistent with the LEM design ΔV budget.

All the ΔV's for the abort transfers are impulsive and are calculated by solving Lambert's problem for the conic trajectory given a transfer time and an initial and final radius. A ΔV of around 600 fps is allowed for aborts off the powered descent prior to phasing for nominal launch conditions. For aborts off the powered descent occurring after this phasing, as well as aborts from the surface, a ΔV of 400 fps is allowed.

Out-of-plane corrections are assumed to be performed at a node between the CSM orbit plane and the LEM transfer orbit plane. An additional ΔV of 48 fps is considered to be conservative for this correction.

All aborts must have a clear pericynthion of 50 000 feet for safety, with the exception of the quick time aborts, for which only an initial positive flight path angle need be assumed. The clear pericynthion trajectories are found by iterating on transfer time. The quick-time aborts are limited to transfer times from 400 to 1200 seconds since times shorter than this would require a continuous powered flight analysis (as opposed to impulsive).

Initial conditions for the orbital flights are established from typical suborbital trajectories exemplified in figure 3 by the altitude

time histories for the powered landing and aborts off this landing. The range angles and flight times for these suborbital trajectories are given in table I.

The reference descent is terminated at 1000 feet. Two minutes of translation and hover time are allowed from this point to the surface. Aborts during this two-minute phase are considered to be the same as surface aborts.

For surface aborts, the time to rendezvous (time in phasing orbit plus transfer time) is assumed to be limited to a 10.5-hour contingency time which is consistent with current LEM life support systems and power system design.

RESULTS

Presented here are the characteristics of the families of orbital transfer trajectories for aborts from the three phases of the LEM mission. These characteristics are ΔV to give an indication of fuel, pericynthion altitude for safety, and total time for life support system design.

Abort Transfers - Hohmann Descent

Two types of transfers are analyzed for aborts from the Hohmann descent; namely, minimum ΔV aborts and quick-time aborts.

The injection velocity ΔV_1 and the rendezvous velocity ΔV_2 of the minimum ΔV abort trajectories off the Hohmann descent transfer are shown in figure 4 as a function of the time from LEM/CSM separation. The time from LEM separation to initiation of the powered descent (pericynthion) is only 0.97 hour or 3484 seconds. However, to investigate the effect of continued coast in the Hohmann transfer orbit beyond pericynthion, separation times up to 2.1 hours are shown. This type of transfer can be made if time is not critical. The results indicate that the ΔV for aborting increases to 480 fps (at pericynthion); however, by coasting beyond pericynthion for another 0.97 hours (apocynthion) the ΔV for aborting is reduced to 270 fps.

The pericynthion altitude, hp, for these transfers is always greater than or equal to 50 000 feet as depicted in figure 5, thus adhering to the clear pericynthion requirement for safety.

The total time of the abort transfer T and the transfer angle θ of the minimum ΔV abort transfers are presented in figure 6 as a function of the time from separation (time of abort). The time to rendezvous is never greater than 2.8 hours, while θ varies from 150° to 350°. The discontinuity around 270 seconds is due to the fact that two "minimum" ΔV aborts occur -- one with a $\theta > 180°$ and the other with a $\theta < 180°$. One of these is a "local minimum", whereas the other is an "absolute minimum". At the 720-second abort time, it happens that the transfer angles of the local and absolute minimum transfers are switching positions ($\theta > 180°$ to $\theta < 180°$). Although the ΔV penalty is less than 1 fps between the local and absolute minimums, the absolute is plotted in each instance, that is, absolute within the pericynthion restrictions imposed.

The results of the quick-time aborts (transfer times from 400 to 1200 sec) are depicted in figure 7. The ΔV_T for each transfer time is varied with the time of abort. There are no pericynthion restrictions on these aborts. The ΔV_T is shown to be as large as 6000 fps for these impulsive transfers. While it is realized that ΔV's of this magnitude cannot be input impulsively, the results do indicate the order of magnitude of the ΔV_T required for specified quick-time aborts. Also, since the ΔV design limits for the descent ($\Delta V = 7400$ fps) and ascent ($\Delta V = 6600$ fps) stages are each greater than the ΔV_T required, then only one of these engines would be required for the quick-time aborts.

Abort Transfers – Powered Descent

The orbital transfers off the powered descent are initialized from the suborbital reference trajectories presented in table I. The ΔV_1 and ΔV_2 for the coasting transfers for aborts during powered descent are shown as a function of time of abort from the beginning of the powered descent (50 000-foot altitude). The total velocity required ($\Delta V_1 + \Delta V_2$) decreases as the LEM descent trajectory approaches the surface. In fact, the abort transfer becomes a Hohmann transfer (same as nominal launch trajectory) for an abort at the 1700-foot altitude point. Aborts below this point are considered to be the same as the surface aborts to be discussed in the next section.

The transfer angle θ and the transfer time T for aborts off the powered descent are presented in figure 9 as a function of the abort time. The transfer angle is shown to vary from 178° to 268° while T ranges from 1 hour to $1\frac{1}{2}$ hours.

Abort Transfers - Surface Aborts

All transfers for surface aborts are referenced to conditions at burnout of nominal launch (50 000 ft). It should be noted that this does not correspond to conditions that exist immediately upon touchdown. It does, however, correspond to conditions for an abort from the 1700-foot altitude point in the descent trajectory; hence, aborts during this last $2\frac{1}{2}$ minutes of the descent are identical to aborts for the first $2\frac{1}{2}$ minutes after nominal launch. A plot of variation of the time to rendezvous (time in phasing orbit plus Hohmann transfer time) with time after nominal launch is shown in figure 10. The time to rendezvous varies linearly from .97 hour to 10.5 hours (contingency limit) for the first 62 minutes of surface stay time. Since the period of the CSM is approximately 2.1 hours, it is obvious then that it will be about another 1.1 hours until the CSM position is again correct for a nominal launch to Hohmann transfer conditions. The results shown in figure 10 are not necessarily the best for time considerations. In fact, after 10.75 minutes stay time, the rendezvous time would be less if the LEM waited for the second pass of the CSM over the landing site and performed an immediate launch to Hohmann transfer conditions. After this point, the time in the phasing orbit is greater than the remainder of the CSM period. However, if the LEM had to leave the lunar surface, Hohmann phasing conditions could be obtained by waiting in the phasing orbit as shown in figure 10, although the rendezvous time would be greater.

Aborts after 1 hour stay time and before 2.1 hours stay time require phasing maneuvers by the CSM as well as the LEM, as discussed in reference 1. However, 4.5 minutes prior to the 2.1-hour stay time, the LEM could abort and perform an intercept transfer other than a Hohmann transfer. In this case, the phase angle at the end of the powered launch would be less than the phase angle necessary for a Hohmann transfer, and since the LEM orbital velocity is greater than that of the CSM, Hohmann phasing conditions could not be obtained within the contingency time by waiting in the phasing orbit, therefore necessitating another type of transfer. Figure 11 shows the transfer angle and rendezvous time as a function of phase angle for these transfers. The variation of ΔV_1, ΔV_2, and ΔV_T with phase angles is shown in figure 12. These are planar transfer requirements (see Scope of Calculations for out-of-plane consideration). The ΔV_T varies from Hohmann impulse of 198 fps to 503 fps (near maximum ΔV available for perfect launch). After this time the ΔV_T becomes prohibitive and CSM phasing maneuvers become necessary. It is to be noted that the abort problem from the lunar surface is of a cyclic nature and the results in figures 10, 11, and 12 will recur at the completion of each CSM orbit.

A summarization of aborts during all 3 phases of the LEM mission is shown in figure 13. Although the chart is terminated at 4.5 hours after the LEM is separated from the CSM, aborts beyond this time are represented by the cyclic pattern occurring between 2.2 and 4.2 hours. The length of this period corresponds to the orbital period of the CSM. This plot depicts only one such period, but the pattern may be repeated for the lifetime of the LEM.

There is a discontinuity in the total ΔV curve at .97 hour, that is, the initiation of the powered descent. A ΔV of 100 fps must be added since aborts from the powered descent terminate at circular orbital conditions, and all other aborts are off the Hohmann descent.

CONCLUDING REMARKS

The results of an investigation of the orbital transfer characteristics for LEM aborts from the Hohmann descent transfer and from circular parking orbits attained after aborting from the powered descent and from the lunar surface have been presented. The variation of the required characteristic velocity and the time required to complete rendezvous indicate that the present allowances of 500 to 600 fps and 10.5 hours contingency time are sufficient for most abort situations. The exception applies to those aborts from the lunar surface initiated between 1.0 and 2.1 hours after the time for a nominal launch. Aborts during this period may not be completed autonomously by the LEM, but require phasing maneuvers by the CSM.

REFERENCE

1. Price, C.; and Bennett, F.: Brief Investigation of CSM Rescue of LEM. MSC Internal Note 64-EG-2, 1964.

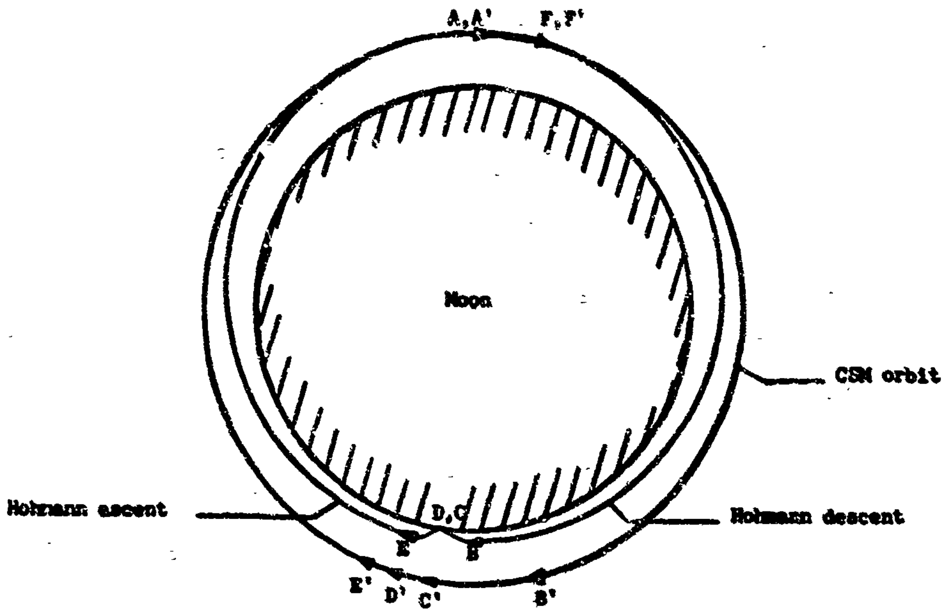
TABLE I.- RANGE ANGLES, FLIGHT TIMES, AND T/W_o

OF REFERENCE TRAJECTORIES

Trajectory	Range angle, deg	Flight time, sec
Powered descent*	11.74	455.1
Abort 37 sec after start of powered descent**	2.06	38.6
Abort 187 sec after start of powered descent	8.69	206.8
Abort 307 sec after start of powered descent	10.65	341.6
Abort 425 sec after start of powered descent	9.96	401.1

*Terminated at 1000 feet altitude with 75 fps horizontal velocity $\left(T/W_o = .35\right)$.

**All aborts and the launch trajectory terminate at 50 000 feet altitude with circular orbital velocity $\left(T/W_o = 35\right)$.



A LEM separation and insertion into Hohmann descent

B Initiation of powered descent

C Hover, translation and touchdown

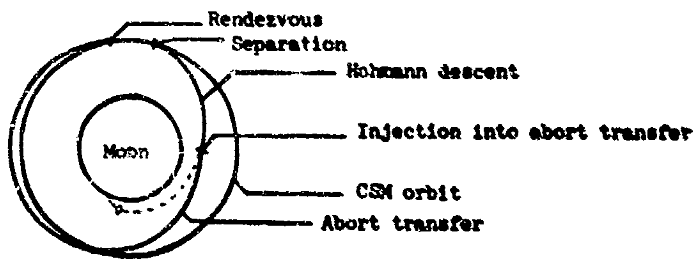
D Launch

E Insertion into Hohmann ascent

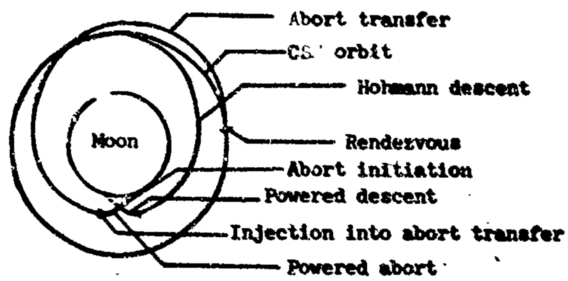
F Terminal rendezvous and docking

(primes denote corresponding position of CSM)

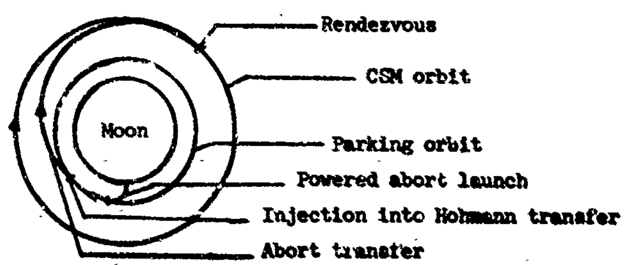
Figure 1.- Nominal LEM mission.



(a) Abort from Hohmann descent



(b) Abort from powered descent



(c) Abort from surface

Figure 2.- Abort phases.

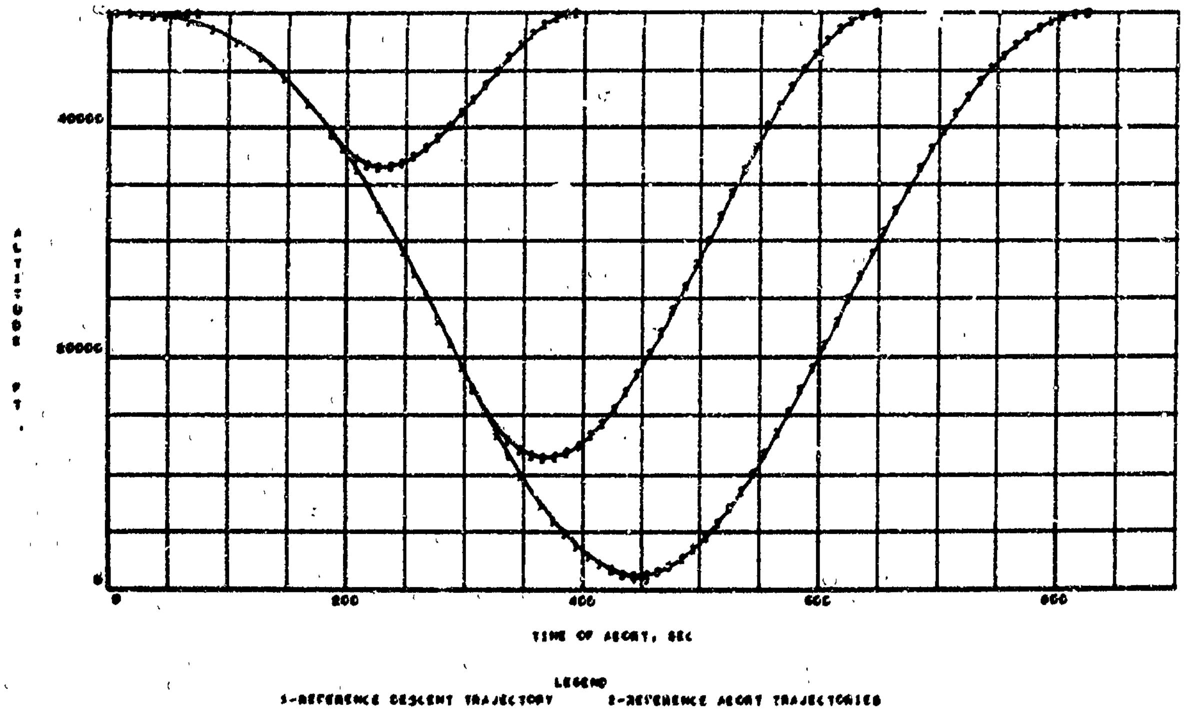


Figure 3.- Reference powered descent and powered abort trajectories.

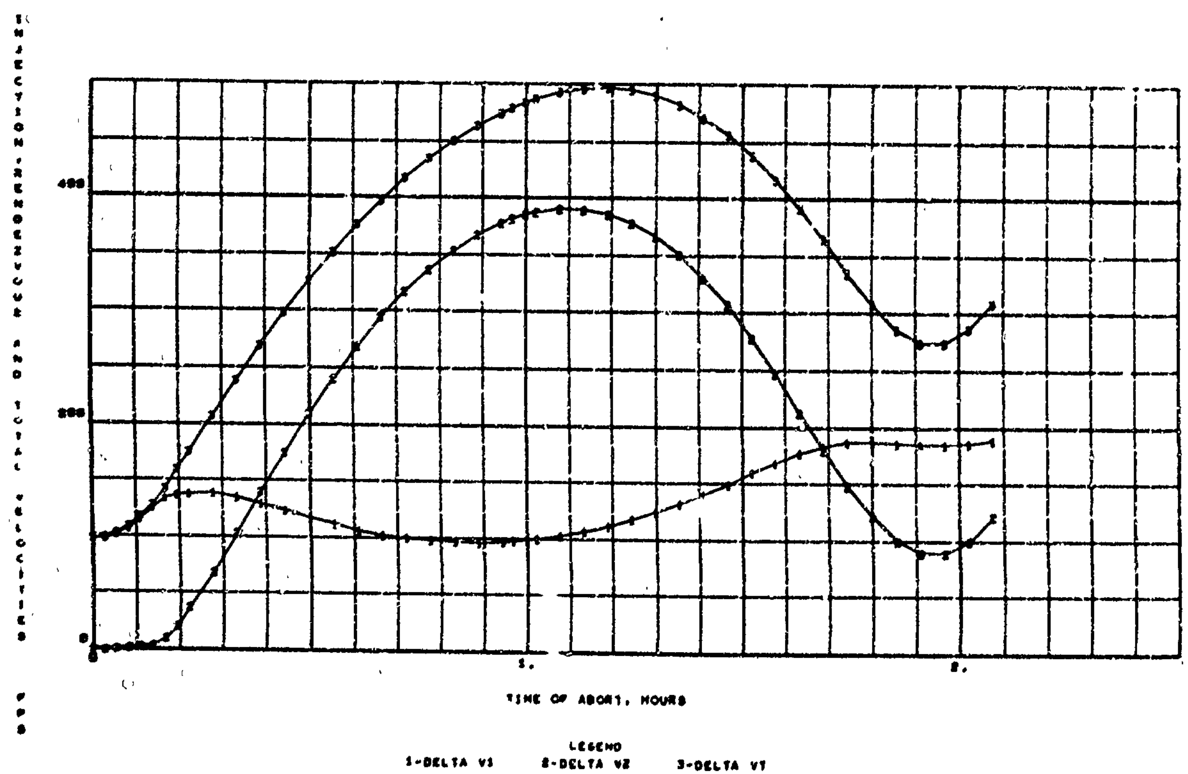


Figure 4.- Variation of ΔV_1, ΔV_2, and ΔV_T with time of abort from Hohmann descent (pericynthion at .97 hr).

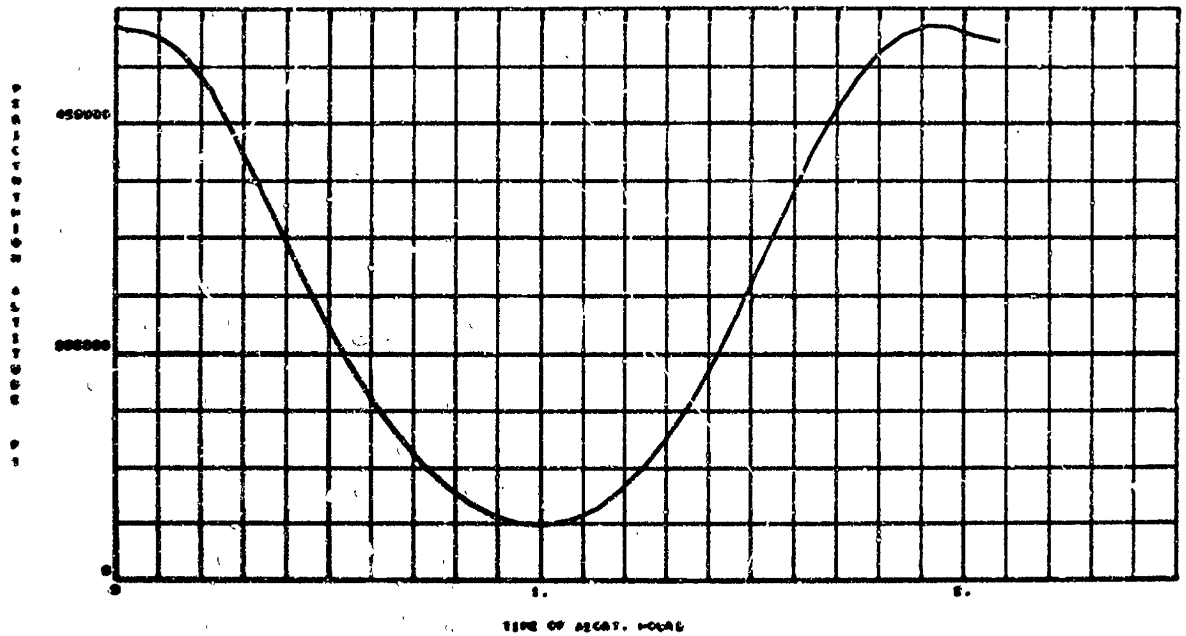


Figure 5.- Variation of pericynthion altitude with time of abort from Hohmann descent.

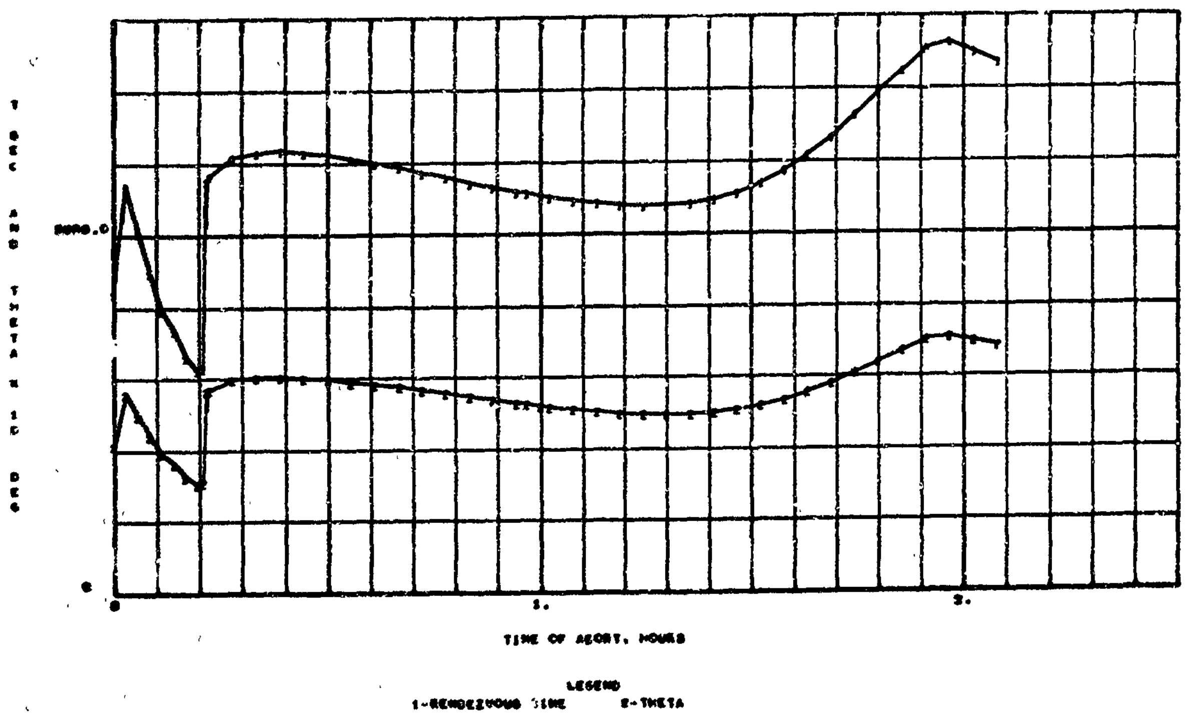


Figure 6.- Variation of rendezvous time and transfer angle with time of abort from Hohmann descent.

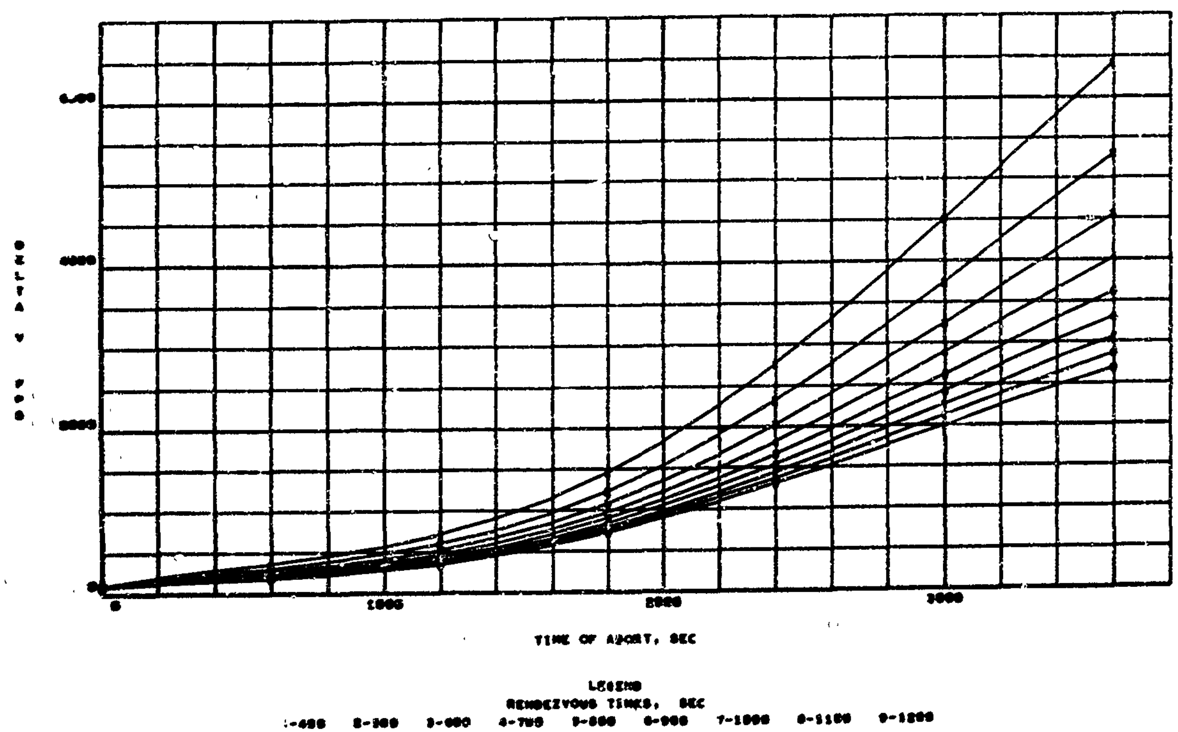


Figure 7.- Variation of total ΔV with time of abort for quick rendezvous from Hohmann descent.

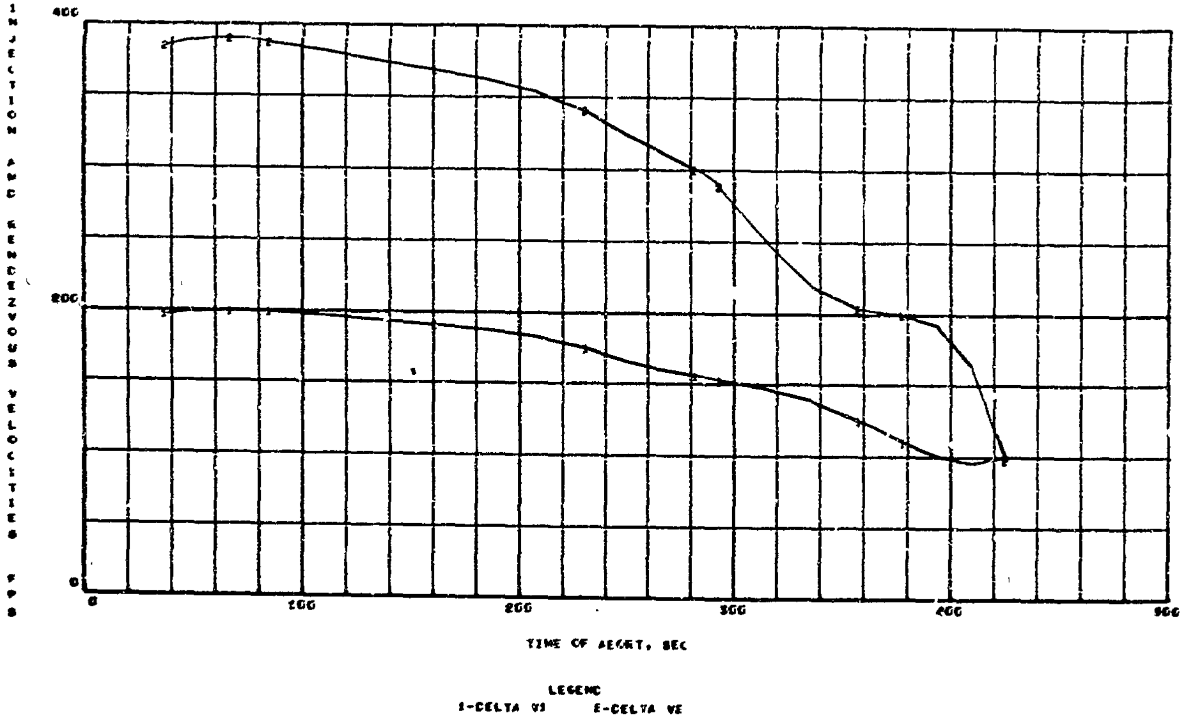


Figure 8.- Variations of ΔV_1 and ΔV_2 with time of abort off powered descent.

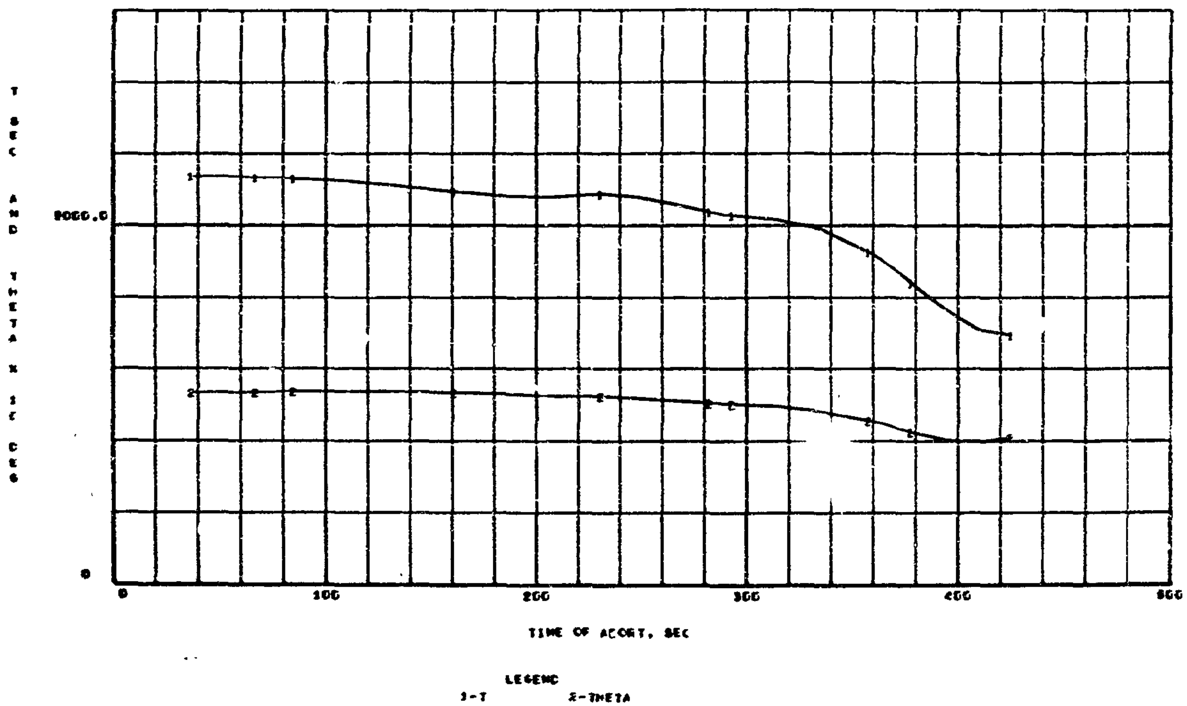


Figure 9.- Variation of rendezvous time and transfer angle with time of abort off powered descent.

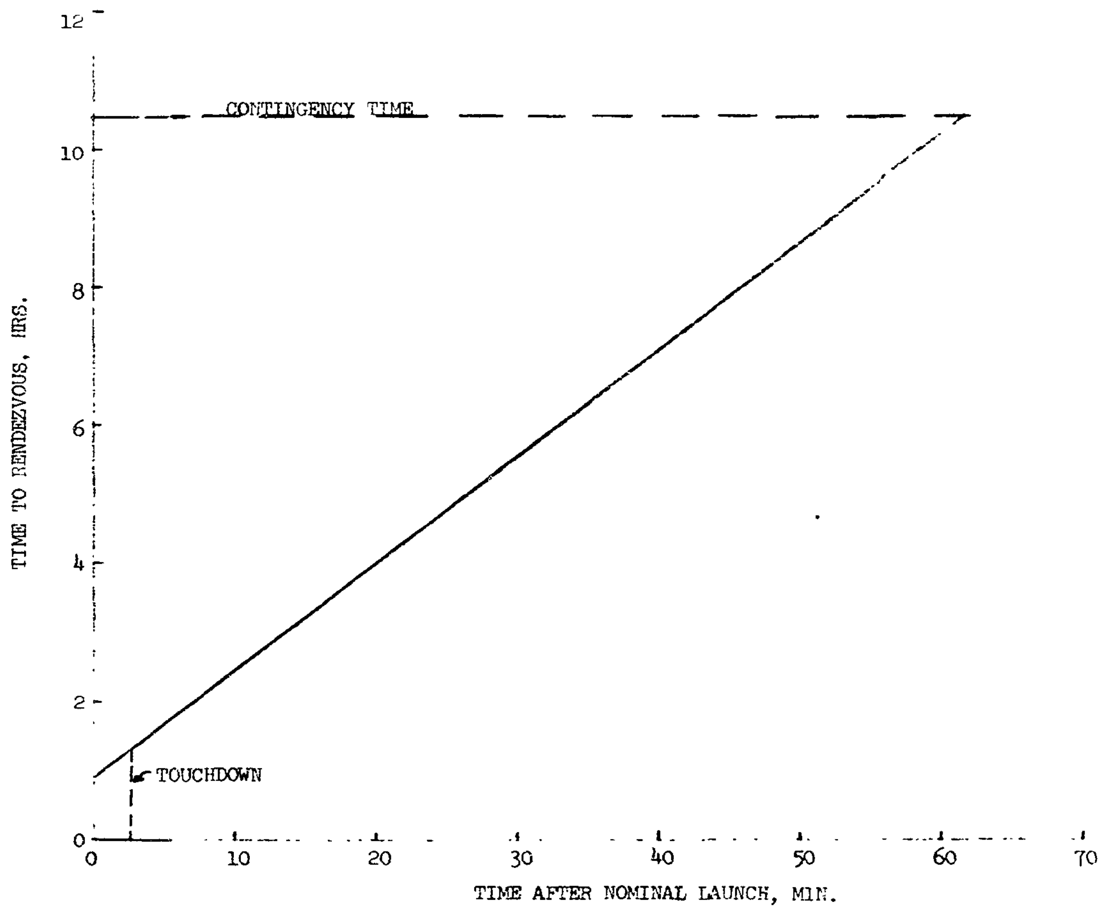


Figure 10.- Variation of time to rendezvous with time after nominal launch for surface aborts.

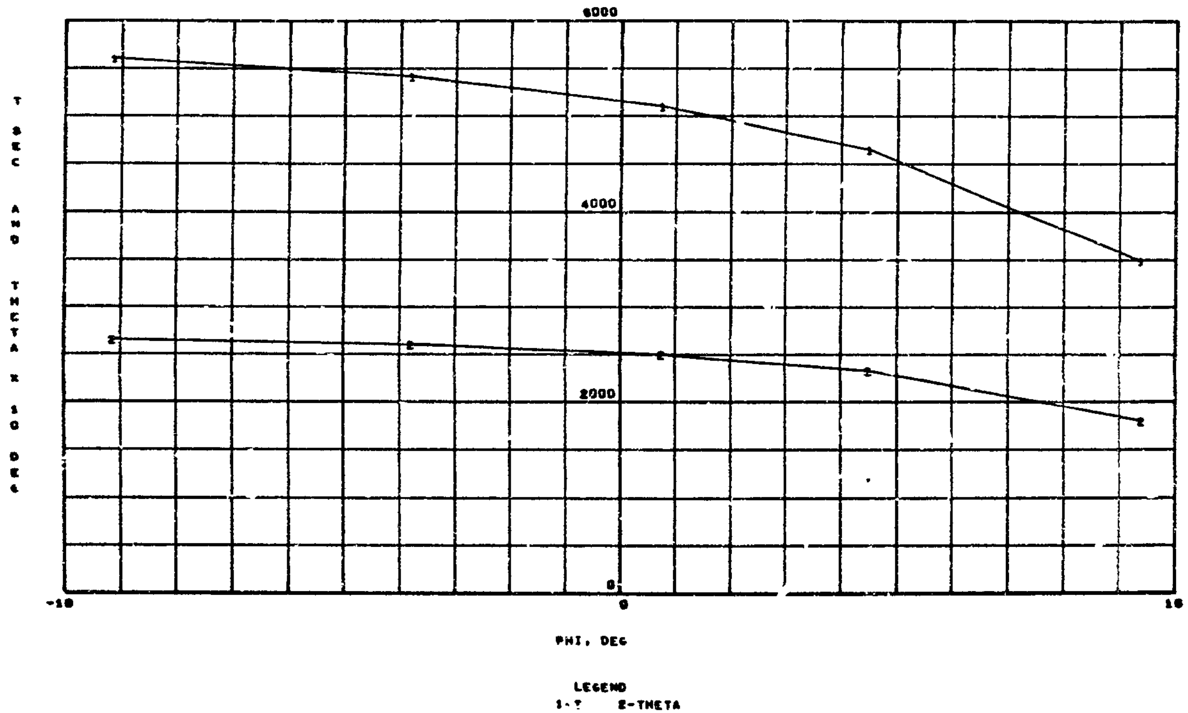


Figure 11.- Variation of θ and time to rendezvous with phase angle for surface aborts.

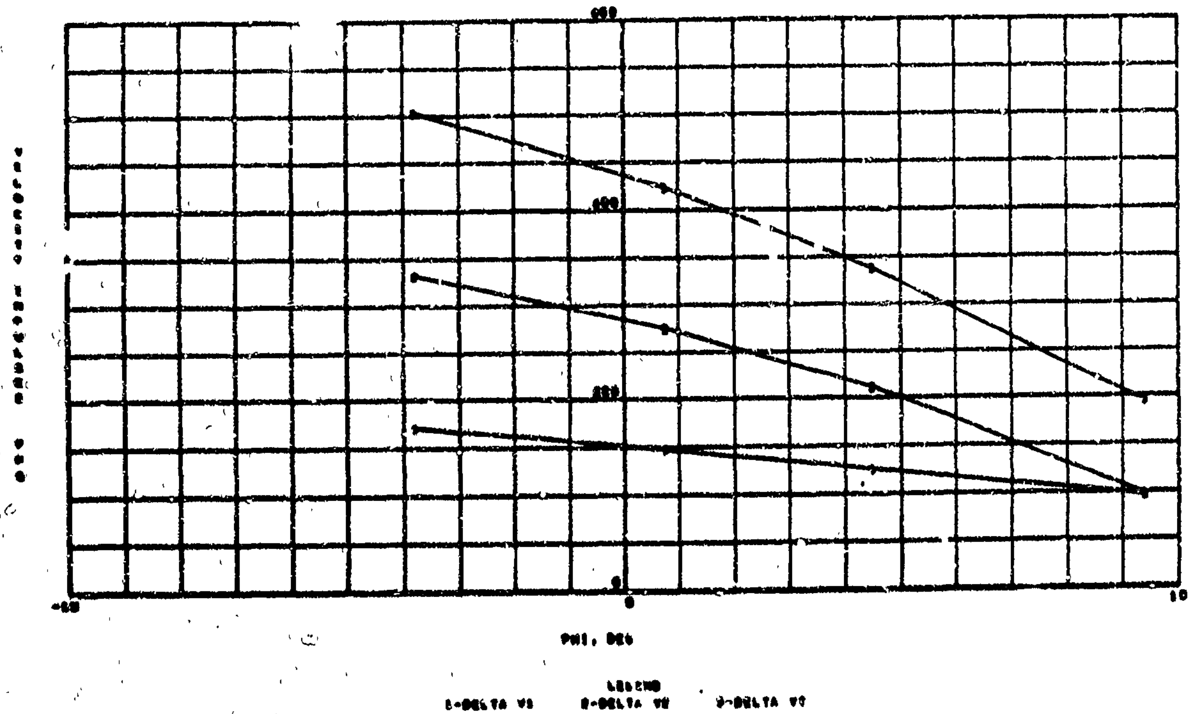
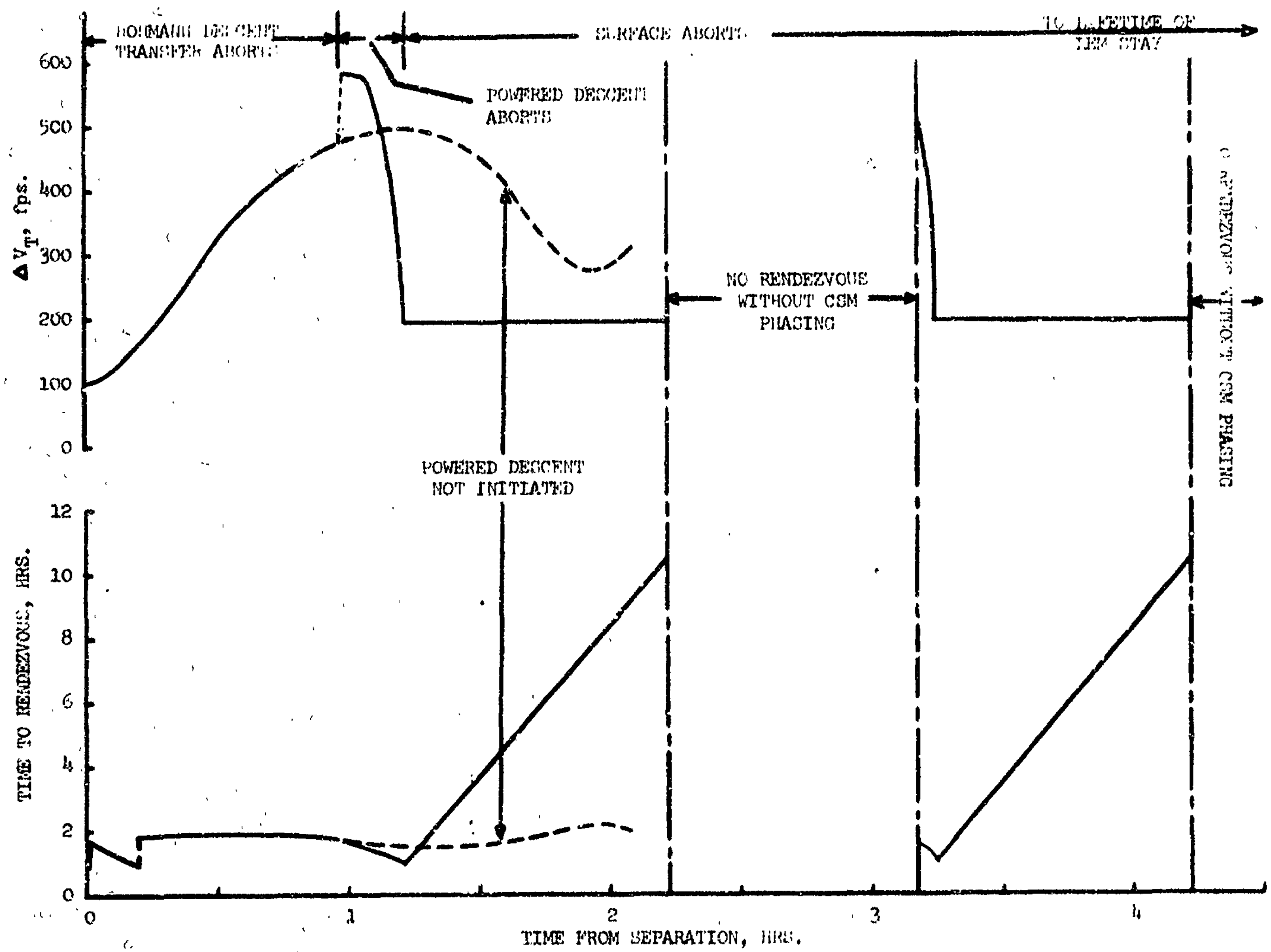


Figure 12.- Variation of ΔV_1, ΔV_2, and ΔV_T with phase angle for surface aborts.



*A ΔV must be added for surface aborts out of CSM orbital plane (48 fps for 1° out-of-plane)

Figure 13.- Summary profile of LEM abort transfer trajectory characteristics.